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Equilibrium Model of Fate of Microcontaminants in Diverse Aquatic Food Chains

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Equilibrium Model of Fate of Microcontaminants in Diverse Aquatic Food Chains

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Bioconcentration and bioaccumulation factors of PCB, ^{239}Pu, and ^{137}Cs are compiled from the literature as a function of organism size. The distribution of field-observed bioaccumulation factors varies markedly between each substance but similarly to order of magnitude within each substance across diverse food chains. It can be inferred from the literature that PCB levels in top predators are due primarily to food chain transfer. A steady state compartment food chain model is derived for estimation of the relative effect of uptake directly from water versus food chain transfer. The model food chain transfer number f, given by $\alpha C/K + G$ for α = chemical absorption efficiency, C = specific consumption, K = excretion rate, and G = net organism growth rate indicates the degree of food chain accumulation. For $f > 1$, food chain transfer is significant; for $f < 1$, uptake from water is more significant. Application of the model suggests that (a) PCB body burden in top predators is due almost entirely to consumption of contaminated prey, (b) for ^{239}Pu all of the body burden is due to uptake from the water only, and (c) observed ^{137}Cs concentration factors are due principally to food chain transfer with a high dependence on the salinity-dependent phytoplankton adsorption.

Key words: food chain model, bioconcentration, bioaccumulation, PCB, ^{239}Pu, ^{137}Cs, water uptake, food chain transfer

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L'auteur a compilé les facteurs de bioconcentration et de bioaccumulation des BPC, de ^{239}Pu et de ^{137}Cs en fonction de la taille des organismes, à partir des données publiées. La répartition des facteurs de bioaccumulation observés sur le terrain varie de façon marquée d'une substance à l'autre, mais aussi en ordre de grandeur, pour une même substance, à travers une chaîne alimentaire diversifiée. On peut déduire des publications que les niveaux de BPC chez les prédateurs supérieurs sont dus principalement au transfert dans la chaîne alimentaire. On a établi un modèle de chaîne alimentaire compartimenté et en état d'équilibre dans le but d'estimer l'effet relatif d'une absorption directe de l'eau versus le transfert dans la chaîne alimentaire. L'indice de transfert dans la chaîne alimentaire f, déduit de $\alpha C/K + G$ où α = l'efficacité d'absorption chimique, C = la consommation spécifique, K = le taux d'excrétion et G = le taux de croissance net de l'organisme, indique le degré d'accumulation dans la chaîne alimentaire. Pour $f > 1$, le transfert dans la chaîne alimentaire est significatif; pour $f < 1$, l'absorption à partir de l'eau est plus importante. L'application du modèle laisse penser que: (a) la charge corporelle de BPC chez les prédateurs supérieurs provient presque exclusivement de la consommation de proies contaminées, (b) quant à ^{239}Pu, toute la charge corporelle est due seulement à l'absorption à partir de l'eau et (c) les facteurs de concentration de ^{137}Cs observés résultent principalement du transfert dans la chaîne alimentaire, avec assujetissement à l'absorption de phytoplancton dépendante de la densité.

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INFORMATION on microcontaminants in aquatic food chains has accumulated over a period of years for a wide variety of water bodies throughout the world. Such data are currently being collected at an ever increasing rate as a result of heightened concern over environmental deterioration. Examples of such concern include PCB contamination of the Hudson River and Great Lakes fisheries (Hetling et al., 1978; Delfino 1978), studies of insecticides, PCB, and metals in African lakes (Greichus et al., 1978) and long-term monitoring of chlorinated hydrocarbons in Lake Paijanne, the second largest

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lake in Finland (Hattula 1978). Concurrently, there is an urgent need to describe cause and effect relationships between discharges of toxic substances and resulting levels in the aquatic food chain. An attempt is made here to collate and evaluate data on potentially hazardous substances using a simplified transfer model. The objective of this work therefore is to use a simple model of chemical distribution in aquatic food chains to estimate expected levels in aquatic organisms under different cases of chemical bioaccumulation. Ultimately, a basis may be provided for the allocation of chemical discharges to meet specified target levels in the food chain.

In addition, there is considerable confusion over the extent to which food chain transfer of chemicals influence the potential for bioaccumulation. For example, Scura and Theilacher (1977) in evaluating laboratory data on transfer of chlorinated hydrocarbons (CHC) with an algal flagellate, rotifer, and anchovy larva food chain concluded that "CHC accumulation is not a food-chain phenomenon but rather the result of direct partitioning of the compounds between the seawater and the test organisms." Macek et al. (1979) in a summary of experimental data concluded that with the exception of DDT, "the process of bion agnification, as classically defined, probably does not occur within communities of aquatic organisms." These evaluations of the significance of food chain accumulation, it should be noted, resulted from laboratory microcosm data of simplified food chains that did not include natural top predators. On the other hand, Weininger (1978) using a model of PCB accumulation in the lake trout of Lake Michigan and comparing the model to observed field data concluded that "Direct uptake of PCBs can only account for 2−3% of total observed PCB accumulation by adult lake trout, although this route is more important for juveniles." These contradictory reports are due in part to the lack of a suitable modeling framework to provide a basis for estimating the relative effect of food chain transfer versus direct uptake from the water.

My intentions are to:

1) collate published data gathered from different ecosystems to search for unifying trends in fate of microcontaminants;
2) present evidence strongly indicative of food chain transfer for a toxicant such as PCB and conversely to present evidence for lack of importance of food chain transfer for certain chemicals;
3) develop a simple food chain model of contaminant transfer;
4) apply the model to some data on chemicals with varying behavior in aquatic ecosystem.

Size-Dependent Food Chain Bioaccumulation

The existing information on microcontaminants in various sectors of the food chain can be organized in a convenient way by relating the toxicant concentration to organism size (or through appropriate allometric relationships to organism wet weight). The use of some measure of the length of an organism serves as a metric for displaying food chain relationships although it is recognized that the size of an organism is not necessarily a good general measure of trophic position (Thomann 1978, 1979). Organism size may be defined in terms of the spherical equivalent of a known mass as in Sheldon et al. (1972) or in this paper simply as a representative size to the nearest order of magnitude. The contaminant concentration can be normalized between ecosystems with the water concentration, by defining

$$(1) \qquad N'(L) = \frac{v'(L)}{c}$$

where v' is the concentration of the toxicant in the organism (μg/g(d))(g(d) = grams dry weight), c is the concentration of the toxicant in the water (μg/g), L is the organism size (μm), and N' is the concentration factor. The difficulty with this normalization is the uncertainty of the water concentration of the microcontaminant. At the low levels of certain contaminants such as the chlorinated hydrocarbons, the analytical difficulty is substantial and analyses from laboratory to laboratory are often inconsistent. For other contaminants, however, such as the radionuclides discussed below, analytical techniques have been developed over several decades and the water concentrations are known with considerable more assurance than contemporary toxicants. The concentration factor on a wet weight basis is given by

$$(2) \qquad N(L) = \frac{v(L)}{c}$$

where v is now μg/g(w), (g(w) = grams wet weight).

Note that

$$(3a) \qquad v'(L) = \beta(L)v(L)$$

and

$$(3b) \qquad N'(L) = \beta(L)N(L)$$

where β is the ratio of wet weight to dry weight. For this work, this ratio was set at 10 (90% water) for the phytoplankton, 5 for the zooplankton, and 4 for the upper levels of the food chain. In Eq. (1) and (2), the water concentration is usually an operationally defined "dissolved" portion (e.g. <0.45 μm or after centrifugation).

A distinction is also necessary between the experimental bioconcentration of a chemical directly from the water, designated herein as N'_u and the bioaccumulation of the chemical under natural field conditions designated N'_f. The latter factor includes the accumulation of the contaminant directly from the water as well as from feeding habits on prey with varying levels of contamination. In general then

$$(4) \qquad \frac{N'_f(L)}{N'_u(L)} \geq 1.$$

If $N'_f = N'_u$, then the effect of food chain transfer is zero, and if $N'_f \gg N'_u$, then the uptake from food consumption must be important. It is useful to compare N'_f to N'_u for different-sized organisms and for several distinct aquatic ecosystems to determine from the data alone whether food chain transfer is of significance. PCB, ^{239}Pu, and ^{137}Cs were chosen to illustrate the varying importance of food chain uptake and because of the existence of a considerable worldwide data base.

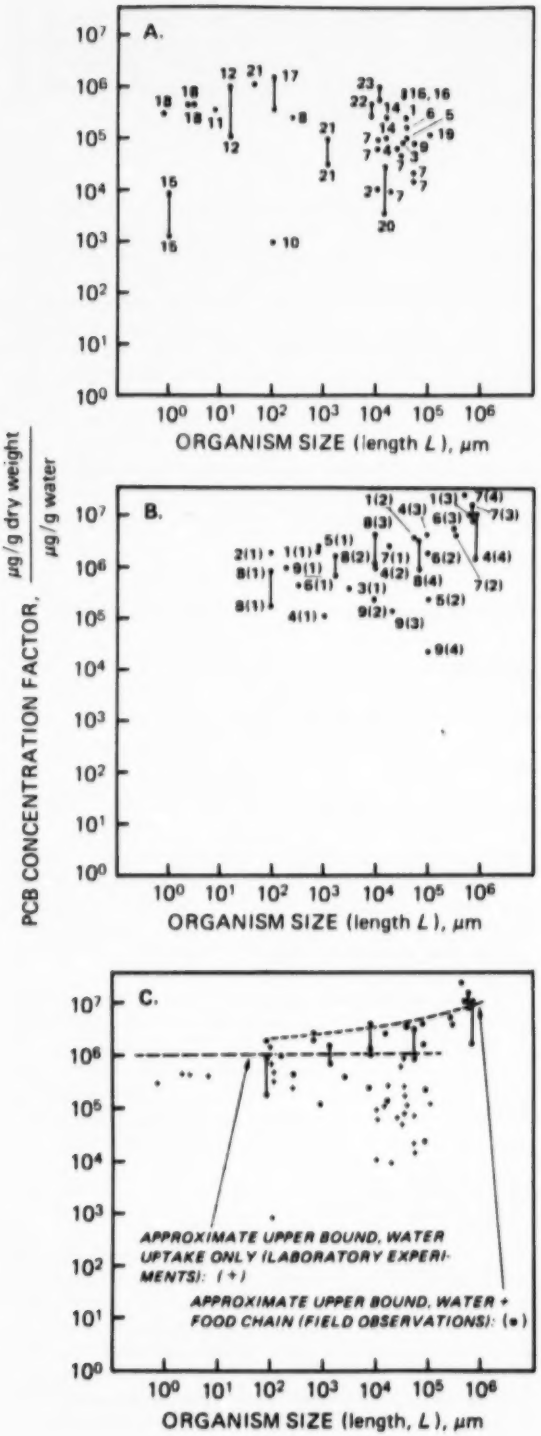
A.
B.
C.
PCB CONCENTRATION FACTOR, μg/g dry weight / μg/g water
ORGANISM SIZE (length L), μm
APPROXIMATE UPPER BOUND, WATER UPTAKE ONLY (LABORATORY EXPERIMENTS): (+)
APPROXIMATE UPPER BOUND, WATER + FOOD CHAIN (FIELD OBSERVATIONS): (•)

FIG. 1(a). PCB bioconcentration factor, (dry weight basis) uptake from water only, see Table 1 for references; (b) observed PCB bioaccumulation factors (dry weight basis) from field measurements; uptake from water and food, see Table 2 for references; (c) comparison of PCB concentration factors from water only to PCB concentration factors under field conditions.

SIGNIFICANCE OF FOOD CHAIN ACCUMULATION OF PCB

The observed behavior of $N'_w(L)$, the bioconcentration due only to uptake of PCB directly from the water, and $N'_F(L)$, the bioconcentration under natural field conditions is plotted against organism size in Fig. 1. (See Tables 1 and 2 for supporting references.)

Figure 1A shows $N'_w(L)$ as calculated from the literature. The scatter is large and no discernible trend is evident. All of the data shown in Fig. 1A were obtained from laboratory aquaria experiments, sometimes not under the best of controlled conditions. Data were used only where the experiment was judged to have reached equilibrium and where it appeared that the reported water concentration was consistent with the above definition of the dissolved fraction. For some experiments, the dissolved fraction was estimated from the total water concentration. In those instances, additional suspended solids may have been generated during the test (through fecal or particle formation, for example) which may have lowered the dissolved component such that N'_w would be overestimated. It should be noted too, that the largest organism used in these experiments is $\sim 10^5$ μm (0.1 m). There is no information on PCB uptake from water for top carnivores such as lake trout or striped bass. With a few exceptions, the experiments used the higher chlorinated isomers or mixtures of PCB, e.g. Aroclor 1254. The approximate upper bound for the bioconcentration factor due to water alone from Fig. 1A is about 10^6 μg/g(d) ÷ μg/g.

Figure 1B shows on comparable scales, the PCB bioaccumulation factors for different-sized organisms from field data for nine water bodies. The greatest uncertainty in the above values is due to the estimate of the dissolved fraction, c. For some areas a reasonable range of values is at hand (e.g. Hudson Estuary and Western Lake Superior). For other regions, e.g. Milwaukee Harbor, an estimate was made based on equilibrium partitioning to a known or assumed level of suspended solids. Figure 1B does appear to indicate an upward trend toward higher $N'_F(L)$ as one proceeds up the food chain. A notable exception is the data for the Mediterranean Sea off the French coast (no. 9 in Fig. 1B) reported by Fowler and Elder (1978). The PCB in that food chain clearly decreases from the microplankton (no. 9 (1)) to the myctophid fish (no. 9 (4)). The upper bound of the data in Fig. 1B, however, indicates a general increase from about 10^6 for the microplankton (100 μm) to greater than 10^7 for the upper levels of the food chain.

Figure 1C combines 1A and B to show more clearly the increasing divergence between N'_F and N'_w indicating an accumulation of PCB with trophic level. At 10^6 μm, for example, the upper bound in the field data is about 10^7 or one order of magnitude greater than the amount of PCB that would be accumulated as a result of uptake from the water alone.

TABLE 1. Explanation of symbols for Fig. 1(a). PCB concentration factors, water only.

No.	Organism or particle type	PCB analyzed	Reference
1.	Spot (*Leiostomus xanthurus*)	Arclor 1254	Moriarty (1975)
2.	Mayfly nymph (*Ephemera danica*)	Clophen A 50	Sodergren and Svensson (1973)
3.	Oyster (*Crassostrea virginica*)	Isomer mixture	Vreeland (1974)
4.	Pinfish (*Lagodon rhomboides*)	Arcoclor 1016	Hansen et al. (1974)
5.	Spot (*Leiostomus xanthurus*)	Aroclor 1254	Duke and Dumus (1974)
6.	Minnow (*Cyprinodon variegatus*)	Aroclor 1254	Hansen et al. (1973)
7.	Aquatic invertebrates; midge, scud, mosquito larvae, stonefly dobsonfly, crayfish	Aroclor 1254	Sanders and Chandler (1972)
8.	Cladoceran (*Daphnia magna*)	Aroclor 1254	Sanders and Chandler (1972)
9.	Pink shrimp (*Penaeus duorarum*)	Aroclor 1254	Nimmo et al. (1971)
10.	Protozoa (*Tetrahymena pyriformis*)	Aroclor 1254	Cooley et al. (1972)
11.	Algae (*Chlorella*)	Clophen A 50	Sodergren (1977)
12.	Marine phytoplankton — natural assemblage	Isomer mixture	Biggs et al. (In prep.)
13.	Illite clay, Woodburn soil	Aroclor 1254	Haque et al. (1974)
14.	Amphipod (*Gammarus*)	Aroclor 1242	Nebeker and Puglisi (1974)
15.	Bacteria, seston and sediment	Aroclor 1016 and 1242	Paris et al. (1978)
16.	Fathead minnow (*Pimephales promelas*)	Aroclor 1242 and 1248	Nebeker et al. (1974)
17.	Centric diatoms	Pentachlorobiphenyl	Harding and Phillips (1978)
18.	Nuchar-Attaclay, sewage microbes, natural particulates	Pentachlorobiphenyl	Harding and Phillips (1978)
19.	Rainbow Trout (*Salmo gairdneri*)	2,2',4,4'-Tetra-chlorobiphenyl	Branson et al. (1975)
20.	Killifish (*Fundulus heteroclitus*)	Tetrachlorobiphenyl	Sugiura et al. (1978)
21.	Copepods (*A. Tonsa*) (*A. Clausi*)	^{14}C-labeled Aroclor 1254	Wyman and O'Connors (1979)
22.	*Skelotonenema*	^{14}C-labeled Aroclor 1254	Wyman and O'Connors (1979)
23.	Fathead minnow (*Pimephales promelas*)	Aroclor 1248 Aroclor 1260	DeFoe et al. (1978)

Additional data are available on PCB levels in top carnivores through extensive field sampling of PCB content in the striped bass of the Hudson Estuary conducted by the New York State Department of Environmental Conservation (NYS DEC) (see Hydroscience 1979). A total of 371 striped bass (largely in the 4−5 year-class) have been analyzed from spring collections during the bass migration period. Quality control was excellent. Three Aroclors were analyzed (1221, 1016, 1254) together with measurements of fresh weight, length, and % lipid for each fish.

Figure 2 shows the cumulative frequency distribution of the log PCB of the Hudson striped bass. The break in the distribution at the 10% level indicates that the density function is bimodal. This may reflect two populations of striped bass; resident and migratory. The median level for the entire population is 10 μg/g(w), but note that the 5% level is 70 μg/g(w), and 2½% of the total population sampled had concentrations of greater than 100 μg/g(w). These latter levels are therefore 7 to 10 times higher than the median level. Also shown in Fig. 2 is the concentration factor for a range of dissolved estuary and near-shore water concentration of 0.01−0.05 μg/L (Hydroscience 1979). A dry to wet conversion factor of four was used. Fifty percent of the fish therefore had concentration factors of $10^{5.9}-10^{6.6}$ or greater. Five percent of the fish had concentration factors of at least $10^{6.75}-10^{7.45}$. These levels are 0.5−1.5 orders of magnitude higher than the levels that have been reported for uptake directly from the water. The difference is ascribed to feeding habits, exposure to higher water concentration than assumed, or a combination of the two. These results indicate the high probability that when a sufficient number of samples is taken, a toxic substance such as PCB can be accumulated to levels significantly greater than would be estimated from laboratory or microcosm experiments.

The Bioaccumulation of Plutonium-239

It is desirable to test and apply the general applicability of any model to as wide a range of conditions as possible. Accordingly, a search was made for microcontaminants that

TABLE 2. Explanation of symbols for Fig. 1(b). PCB bioaccumulation factors, field observed.

Number	Location and organism,	Reference
	Lake Ontario	
1(1)	Net plankton (>64 μm)	Haile et al. (1975)
1(2)	Alewife	Risebrough (1976)
1(3)	Coho	Veith (1976a)
	Milwaukee River	
2(1)	Net plankton	Veith (1970)
	Puget Sound	
3(1)	Zooplankton	Pavlou and Hom (1978)
	Hudson River Estuary	
4(1)	Macroinvertebrates	Hetling et al. (1978)
4(2)	Small (<300 μm) fish	Hydroscience (1978)
4(3)	Largemouth bass (*Micropterus salmoides*)	Hydroscience (1979)
	Adult striped bass (*Morone saxatilis*)	
	N.W. Med. (Ligurian Sea)	
5(1)	Microplankton	Elder and Fowler (1977)
5(2)	Euphausiid	
	Western Lake Superior	
6(1)	Zooplankton (*Mysis relicta*)	Veith et al. (1977)
6(2)	Sculpin	Swain (1977)
6(3)	Pelagic fish	
	Lake Michigan	
7(1)	*Pontoporeia affinis*	Peterson and Ellarson (1978)
7(2)	Bloater chub (*Hybopsis plumbea*)	Swain (1978)
7(3)	Coho (*Oncorhynchus kisutch*) and lake trout (*Salmelinus namaycush*)	Weininger (1978)
	Oldsquaw duck (*Clangula hyemulis*)	Peterson and Ellarson (1978)
	South Swedish Lake	
8(1)	Seston	Sodergren (1973)
8(2)	Zooplankton (>200 μm)	
8(3)	Invertebrates, leeches, detritus feeders	
8(4)	Fish	
	Med. Coast France	
9(1)	Microzoopl. (>76 μm)	Fowler and Elder (1978)
9(2)	Euphausiid	
9(3)	Shrimp	
9(4)	Myctophid fish	

would display markedly different behavior than PCB. Information on ^{239}Pu, a radionuclide generated from weapons testing, provides such an example. A considerable effort has been expended worldwide in measuring the bioaccumulation of ^{239}Pu between the water column, sediments, and biota of major water bodies. The laboratory data base on bioconcentration of ^{239}Pu from the water, however, is not as extensive, and a review is given under Model Calibration. The general trend of the ^{239}Pu bioaccumulation factor is downward as one proceeds up the food chain (Fig. 3, Table 3). A decrease of approximately four orders of magnitude is observed from the lower levels of the food chain ($N = 10^4$) to the top predator of 10^6 μm ($N = 10^0$). At any level in the food chain, the variation is about one to two orders of magnitude, but in all ecosystems the general downward trend is similar.

THE BIOACCUMULATION OF CESIUM-137

Field values for Cesium-137 content in organisms provide a final example (Fig. 4, Table 4). The influence of salinity on the cesium uptake is pronounced. The bioaccumulation factors are reduced in saline water due to the higher concentrations of potassium, which is similar in chemical structure to cesium. Vanderploeg et al. (1975) have compiled information on water uptake of cesium and have discussed and quantified the effect of different potassium levels on cesium

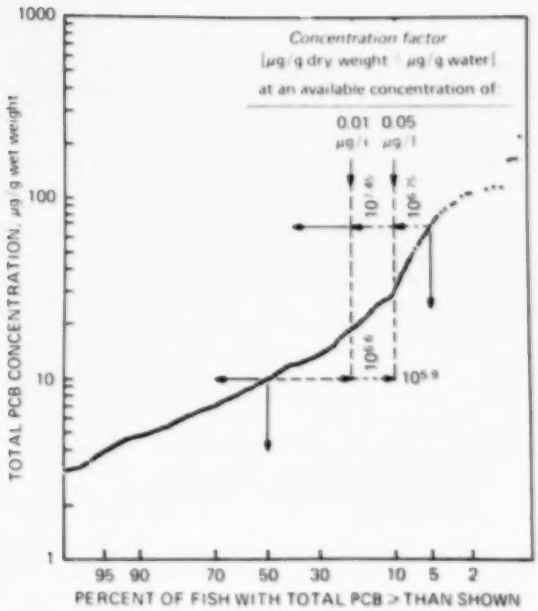

FIG. 2. Frequency distribution of log PCB of Hudson Estuary striped bass, spring 1978 (Data of New York State, Dept. of Env. Cons.).

uptake. The bioconcentration of ^{137}Cs is reviewed under Model Calibration.

The general shape of the cesium food chain distribution represents an intermediate between PCBs and ^{239}Pu. Freshwater concentration factors vary from about 10^3 at the phytoplankton level to about 10^4 at the top predator level indicating some potential for bioaccumulation. It is rather interesting that discrete ecosystems such as freshwaters (Lake Michigan), the Hudson Estuary, and other smaller ponds and lakes all have a similar ^{137}Cs concentration factor relationship with organism size. This suggests that a mathematical framework may be constructed that incorporates the fundamental features of food chain transfer of a contaminant as well as physical uptake in exploring the observed concentration factors.

Simplified Model of Toxicant in Aquatic Food Chain

Although the distribution of a microcontaminant in the food chain can be described by using organism size as a continuous independent variable (Thomann 1979), the biological meaning of the coefficients in such a representation is not entirely clear. The discrete version of the continuous food chain model is a representation of compartment models of the food chain where a compartment is defined in specific biological terms. This latter approach is taken here in the development of a simplified model.

A substantial literature exists on compartment models for transfer of material through food chains and food webs and the related transfers of material. The ecological concepts of compartment analyses have been reviewed by Dale (1970) and Patten (1971) and examples of compartment models include Gillet (1974), Hill et al. (1976), Lassiter et al. (1976), Hoefner and Gillet (1976), and Aoyama et al. (1978). These approaches, however, tend to be somewhat complex in attempting to incorporate a variety of mechanisms or time-variable behavior. A great deal of flexibility is therefore realized in these models for detailed examination of specific problems. On the other hand, complexity sometimes obscures the basic relationships indicated by the preceding data. A simplified model is presented here that incorporates the basic features of the more complex model, but in a steady state condition for a linear food chain. To provide a first level of understanding of the mechanisms that are contributing to the observed concentration factors, a simple four-level food chain model can be considered. Figure 5 shows the schematic of the compartments:

1) Phytoplankton (less than 100 μm);
2) zooplankton (> 100 μm, < 300 mm);
3) small fish (approximately less than 300 mm);
4) large fish (top predator of size 0.1–1.0 m);

and mechanisms or processes in the model:

1) Sorption or direct uptake of the chemical from the water;
2) desorption and excretion of the chemical from the organism;
3) consumption of contaminated food;
4) respiration rate of organism.

Mechanisms (3) and (4) influence the weight change or growth of the organism as a function of age. The estimation of the available concentration of the contaminant in the water phase may be carried out through a separate model of the physical–chemical interactions of the particulate and dissolved components.

In the construction of the food chain model, a mass balance equation is written around each of the compartments incorporating the preceding mechanisms. The mass balance equation represents the flows of the chemical into and out of the average organism. Care must be taken to include the weight change of the organism since such changes affect the chemical concentration.

PHYTOPLANKTON

Consider the phytoplankton, detrital organic material, and other organisms, all of size <100 μm as the base of the food chain. An equation for this compartment is given by a simple reversible sorption–desorption linear equation as:

$$\frac{dv_1}{dt} = k_{a1}c - K_1 v_1 \tag{5}$$

where v_1 is the chemical concentration in the phytoplankton (μg/g(w)), k_{a1} is the uptake sorption rate (L/d-g(w)), K is the desorption and excretion rate (d^{-1}) and c is the concentration of the dissolved form of the chemical in water (μg/L).

GENERAL EQUATION FOR FEEDING COMPARTMENTS

For any food chain compartment that may accumulate the contaminant via ingestion as well as by sorption, a general mass balance equation for the linear food chain in Fig. 5 is

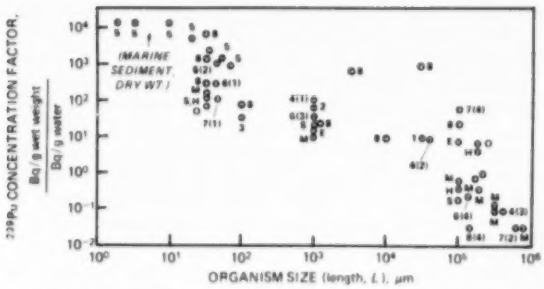

FIG. 3. Plutonium-239 bioaccumulation factors (wet weight basis) from field measurements. See Table 3 for key and references.

obtained as

$$(6)\quad \frac{dv''_i}{dt} = \frac{d(vw)_i}{dt} = \frac{w_i dv_i}{dt} + \frac{v_i dw_i}{dt} = k_{wi} w_i c - K_i v''_i + \alpha_{i,i-1} C_{i,i-1} v_{i-1} w_i \quad i = 2,3,4$$

where v''_i is the average chemical whole body burden (μg) and is given by

$$(7)\quad v''_i = v_i w_i$$

where v_i is chemical concentration in the ith compartment (μg/g(w)), w_i is the weight of the average individual (g(w)), k_{wi} and K_i are, as before, the uptake or sorption rate and desorption and excretion rate, respectively, for the ith organism, $\alpha_{i,i-1}$ is the chemical assimilation efficiency (μg chemical absorbed/μg chemical ingested), $C_{i,i-1}$ is the weight-specific consumption of organism i on $i-1$ (g(w) prey/g(w) pred.-d), and t is real time (days). The assimilation efficiency, α, represents that portion of the ingested contaminant mass that is absorbed and incorporated in organism tissue. The quantity $1 - \alpha$ then represents that portion of ingested chemical which is immediately or rapidly egested by the organism and never accumulated in body tissue. The excretion rate therefore in Eq. (6) is interpreted as excretion and desorption of the chemical that has been sorbed onto or into the organism.

An equation for the individual organism weight is

$$(8)\quad \frac{dw_i}{dt} = (a_{i,i-1} C_{i,i-1} - r_i) w_i, \quad i = 2,3,4$$

where $a_{i,i-1}$ is the biomass assimilation efficiency (g(w) Pred./g(w)prey) and r_i is the weight loss (d^{-1}) due to routine

TABLE 3. Explanation of symbols for Fig. 3. ^{239}Pu concentration factors, field observed.

Symbol	Location and organism	Reference
1	Cape Cod: mussel, clam	Noshkin (1972)
2	Ocean: zooplankton	Noshkin (1972)
3	Ocean: phytoplankton	Noshkin (1972)
	Coastal	
4(1)	Mixed zooplankton	Pillai et al. (1964)
4(2)	Mussels	
4(3)	Bonito (*Sanda sanda*)	
	Irish Sea	
5	Sediment	Hetherington (1978)
	Rocky Flats, Utah	
6(1)	Algae	Thompson (1975)
6(2)	Seston	
6(3)	Zooplankton and crayfish	
6(4)	Bullhead minnow (*Pimephales notatus*)	
	No. East Irish Sea	
7(1)	Algae	Hetherington et al. (1975)
7(2)	Plaice	
7(3)	Salmon	
7(4)	Mussels	
	Laurentian Great Lakes[a]	
S,M,H,E,O, $10^{1.5}$ μm	Phytoplankton and particulates	Marshall et al. (1975)
10^3 μm	Zooplankton	
10^5 to 10^6 μm	Alewife (*Alosa pseudoharengus*), coho, lake trout	
	"U" Pond	
8	A freshwater pond ecosystem, WA.	Emery and Klopfer (1977)

[a]S = Lake Superior, M = Lake Michigan, H = Lake Huron, E = Lake Erie, O = Lake Ontario.

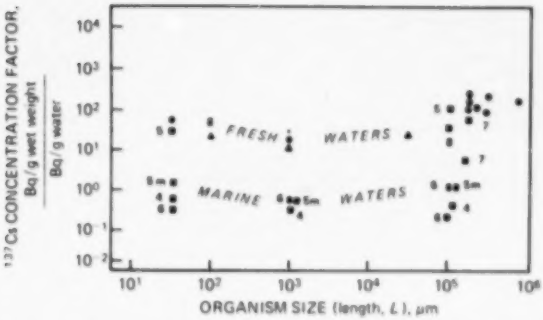

FIG. 4. Cesium-137 bioaccumulation factor (wet weight basis) from field measurements. See Table 4 for key and references.

TABLE 4. Explanation of symbols for Fig. 4. ^{137}Cs concentration factors, field observed.

Symbol	Location	Reference
0	Lake Michigan	Marshal et al. (1975)
Δ	Hudson Estuary	Mauro (1973)
+	Compilation of variety of water bodies	Vanderploeg et al. (1975)
4	Marine environment	Bowen et al. (1971)
5m	Marine environment	Jinks and Eisenbud (1972)
5	Fresh water bodies	Jinks and Eisenbud (1972)
6	Med. Sea, Israeli Coast	Gilat et al. (1975)
7	E. German Waters (fresh and marine)	Ettenhuber and Rohnsch (1975)
8	Par Pond, GA	Harvey (1964)

metabolism, swimming, and other activities. The weight change is therefore

$$(9) \qquad G_i = \frac{dw_i}{dt}/w_i = a_{i,i-1}C_{i,i-1} - r_i.$$

Equation (6) can therefore be written as

$$(10) \qquad \frac{dv_i}{dt} = k_{ai}c + \alpha_{i,i-1}C_{i,i-1}v_{i-1} - K'_i v_i, \qquad i = 2,3,4$$

where

$$(10a) \quad K'_i = K_i + (dw_i/dt)/(w_i) = K_i + G_i.$$

Equations (10) and (10a) together with Eq. (8) and (9) form the basic mass balance chemical equations. The first term of Eq. (10) represents the direct uptake of the chemical by the organism from the water. The second term represents the flux of the chemical into the organism through feeding. Note that the units of this term are gram of chemical assimilated per gram predator per day. The third term is the loss of chemical due to desorption and excretion from body tissue at a rate K_i plus the change in concentration due to growth of the individual. This is reflective of the changing weight available through the size of the organism to "dilute" the concentration of the chemical. The equation pair, (9) and (10), can be solved analytically for the case of known food concentration and constant coefficients or numerically for time-variable coefficients. Norstrom et al. (1976) and Weininger (1978) are examples; in each case, however, the food toxicant concentration is assumed known. To obtain additional insight into the food chain transfer process, it is informative to consider a steady-state analysis of Eq. (10).

EQUILIBRIUM (STEADY STATE) CONDITION

The ith compartment around which the mass balance is taken to derive Eq. (6) is defined as a given age-class of an organism in the food chain. The properties of that age-class include the weight change as a result of net growth, as shown in Eq. (8). The net growth rate of the age-class can be considered to be a constant in time, i.e. that the average growth rate of a 2- to 5-yr-old top predator is the same from 1 year to the next. This assumption implies no temporal change in the feeding rate, food availability or respiration rate. Such an assumption may be entirely reasonable for the lower levels of the food chain but may be questionable for the top predators. Nevertheless, considerable insight can be gained into the behavior of the contaminant equations by assuming a constant growth rate. In a similar fashion, the assumption is made that the uptake, assimilation, and excretion rates are constant within a defined age-class (i.e. a defined compartment).

The solution to Eq. (9) for constant coefficients is

$$(11) \qquad w_i = w_{oi} \exp(G_i t)$$

where w_{oi} is the initial weight at the beginning of the age-class i.

The solution to Eq. (6), the body burden equation under an assumption of constant coefficients, is

$$(12) \qquad v''_i = \frac{(k_{ai}c + \alpha_{i,i-1}C_{i,i-1}v_{i-1})w_{oi}}{K'_i} (\exp(G_i t) - \exp(-K'_i t)) + v''_{oi} \exp(-K'_i t)$$

where v''_{oi} is the initial contaminant body burden at the beginning of the age-class i.

The solution to Eq. (10) is

$$(13) \qquad v_i = \frac{k_{ai}c + \alpha_{i,i-1}C_{i,i-1}v_{i-1}}{K'_i} (1 - \exp(-K'_i t)) + v_{oi} \exp(-K'_i t).$$

Figure 6 shows the form of Eq. (11)–(13). The increase in the weight of the given age-class is exponential as shown in Fig. (6a), with a constant net growth rate of G_i. Figure (6b) shows the increase in body burden and indicates that no equilibrium is reached, i.e. the total mass of contaminant in the organism continues to grow as a result of uptake, assimilation, and increase in weight. Indeed, Eq. (12) shows that only if the net growth rate is zero (i.e. weight of the organism is a constant) is there an equilibrium condition on the body burden. A constant weight assumption, however, is a particularly poor one. Figure (6c) shows that even as weight is increasing exponentially and the body burden increasing according to Eq. (12), the concentration of the contaminant

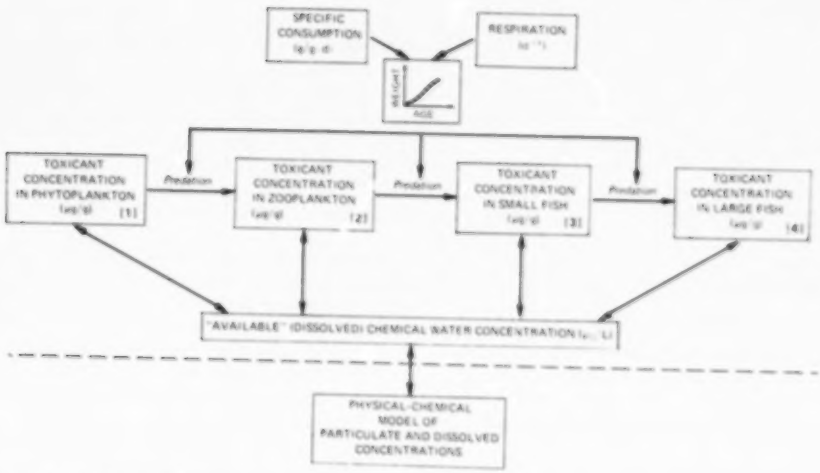

FIG. 5. Schematic of four-compartment food chain model.

approaches a constant value, an equilibrium or steady state condition. This equilibrium concentration represents a balance between the inputs of the contaminant to the organism and the mechanics of excretion and increasing weight of the organism. This can be seen from Eq. (10) where at equilibrium, $dv_i/dt = 0$, and

$$K'_i v_i = k_{ui} c + \alpha_{i,i-1} C_{i,i-1} v_{i-1}$$

or

$$(14) \qquad v_i = \frac{k_{ui} c + \alpha_{i,i-1} C_{i,i-1} v_{i-1}}{K'_i}$$

which can also be obtained from Eq. (13) at large t.

If then it is assumed that the growth and contaminant coefficients are constant over the length of time defined by the age-class of the compartment, then an equilibrium or steady state condition in the concentration of the contaminant is reached. This is the basis of considering an equilibrium or steady state model where the time derivative in Eq. (10) is set equal to zero.

One can also obtain from this line of reasoning the appropriate age-class interval for each compartment that will guarantee an approximate equilibrium condition. If a criteria of 90% of equilibrium is chosen, then the age interval t_a for a compartment is

$$(15) \qquad t_a \geq 2.3/K'.$$

For example, for a low excretion rate (e.g. $K = 0.001$/d) and a high net growth rate that is representative of the lower levels of the food chain (e.g. $G = 0.01$/d), $t_a \geq 209$ d. For a similar excretion rate but reduced net growth that is representative of the upper level of the food chain (e.g. $G = 0.001$/d) then $t_a \geq 3.1$ yr. Therefore if one considers the lower level to be representative of an age-class spanning about 0.5 yr and the upper food chain level to be representative of an age-class spanning about 3 yr, then an equilibrium, steady state concentration will be reached. Such a concentration will be approximately independent of the initial concentration at the beginning of the age-class as can be determined from Eq. (13). On the other hand, if excretion is very low, say approximately zero, and if the net weight change G is also very low, say approximately zero, then Eq. (15) indicates that the age span approaches infinity. This simply implies that an equilibrium condition will never be reached under those compartment characteristics. Such cases can occur for low excretion rates and older top predators, and therefore those situations are specifically excluded from the following steady state model. To summarize, equilibrium or steady state implies constant positive net weight change and constant uptake, assimilation, and excretion rates over an age-class interval defined to guarantee 90% of equilibrium. Each equation of the food chain can now be examined under these conditions.

Zooplankton — In Eq. (5) and (10) if $dv_i/dt = 0$, the steady state equation for the second (zooplankton) compartment is

$$(16) \qquad v_2 = \frac{k_{u2} c + \alpha_{21} C_{21} v_1}{K'_2}.$$

The concentration factor N_2 is then given from Eq. (2) as

$$(17) \qquad N_2 = N_{2w} + \frac{\alpha_{21} C_{21} N_{1w}}{K'_2}$$

where

$$(17a) \qquad N_{1w} = k_{u1}/K_1$$

and

$$(17b) \qquad N_{2w} = k_{u2}/K'_2.$$

Equations (17a) and (17b) represent the bioconcentration factors due to water uptake only. The total zooplankton bioaccumulation factor is thus composed of two parts: that due to direct sorptive uptake from the water and that due to predation

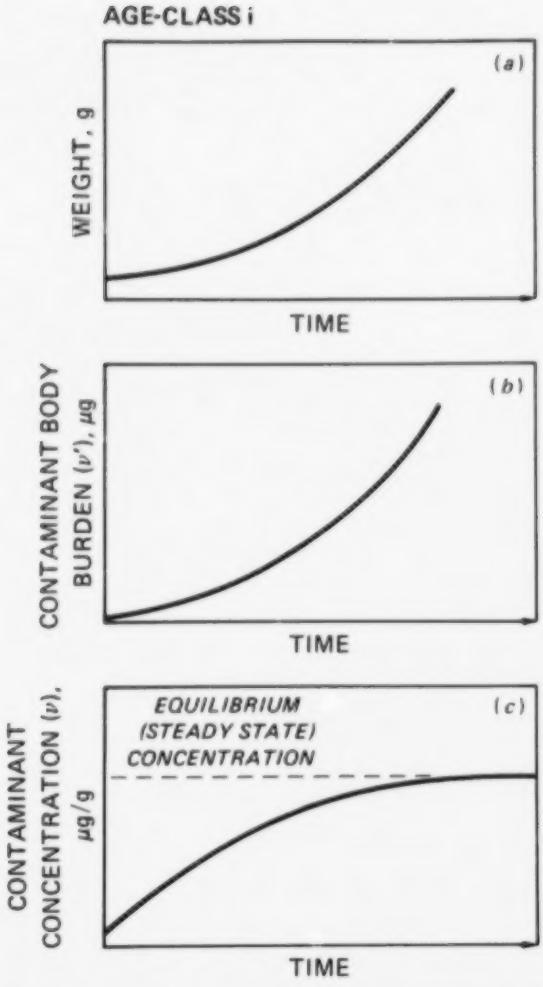

FIG. 6. Illustration of equilibrium conditions for concentration of contaminant in organism. (a) Exponential increase in organism weight, Eq. (11); (b) increase in contaminant body burden, Eq. (12); (c) increase in contaminant concentration to equilibrium (steady state) level, Eq. (13).

on contaminated phytoplankton.

Small fish — Following a development similar to the zooplankton, the steady state equation for the third compartment (small fish) is

$$(18) \quad \nu_3 = \frac{k_{w3}C + \alpha_{32}C_{32}\nu_2}{K'_3}.$$

Substituting Eq. (16) and solving for the small fish bioaccumulation factor gives

$$(19) \quad N_3 = N_{3w} + \frac{\alpha_{32}C_{32}}{K'_3}N_{2w} + \frac{\alpha_{32}C_{32}}{K'_3}\frac{\alpha_{21}C_{21}}{K'_2}N_{1w}$$

where $N_{3w} = k_{w3}/K'_3$, the bioconcentration factor for uptake of the chemical from the water only by the small fish. At this third level, the bioaccumulation factor is now seen to depend on the two lower levels through successive predation.

Large fish — For the top carnivore compartment, the procedure is now direct. The steady state toxicant concentration equation is

$$(20) \quad \nu_4 = \frac{k_{w4}C + \alpha_{43}C_{43}\nu_3}{K'_4}.$$

When successive substitutions are made for each of the lower trophic levels, the resulting bioaccumulation factor for the large fish is

$$(21) \quad N_4 = N_{4w} + \frac{\alpha_{43}C_{43}}{K'_4}N_{3w} + \frac{\alpha_{43}C_{43}}{K'_4}\frac{\alpha_{32}C_{32}}{K'_3}N_{2w} + \frac{\alpha_{43}C_{43}}{K'_4}\frac{\alpha_{32}C_{32}}{K'_3}\frac{\alpha_{21}C_{21}}{K'_2}N_{1w}$$

where $N_{4w} = K_{w4}/K'_4$. The additive effect of each of the lower three trophic levels on the top trophic level is indicated by this equation. It is not clear, of course, from this equation that there is a magnification of the contaminant from the lower to the upper trophic levels. Such a possibility depends on the ratio of the net assimilation of the chemical to the desorption and excretion and net weight change.

General Steady State Case and Further Simplification

The steady state bioaccumulation factor for the nth compartment in a linear food chain can then be written as

$$(22) \quad N_n = N_{nw} + \sum_{j=1}^{n-1}\left(\prod_{i=j+1}^{n} f_{i,i-1}\right)N_{jw}$$

where

$$(23) \quad f_{i,i-1} = \frac{\alpha_{i,i-1}C_{i,i-1}}{K'_i}.$$

The quantity f represents the potential relative increase or decrease in the bioaccumulation factor due to feeding on contaminated prey. Thus, f can be called the food chain transfer number. The quantity $\prod f_{i,i-1}$ is the accumulated effect of the transfer through the $n-1$ levels and may be called the food chain multiplier, designated as Γ. The bioaccumulation factor therefore at any level of the food chain depends on several parameters which reflect the nature of the food chain and the properties of the chemical.

Consider now a further simplification. For convenience, let the food chain transfer number be a constant across the entire chain. Then

$$(24) \quad N_n = N_{nw} + \sum_{j=1}^{n-1} f^{n-j}N_{jw}$$

and the food chain multiplier Γ is simply

$$(25) \quad \Gamma = f^{n-j} = f^x$$

where $x = n - j$ is the number of levels in the food chain

below a given level of interest. Note also that $\log \Gamma = (n - j) \log f$ so that the food chain multiplier is linear in logarithms to the number of passes through the chain. Now it is clear that if $f < 1$, Γ decreases with increasing $n - j$. Figure 7 shows this result for $f = 0.5$ and 0.1. The decrease means that if the uptake due to feeding is less than the overall loss rate, then the upper levels of the food chain do not "feel" the chemical concentrations from compartments several levels below it. For this case the chemical concentration of the phytoplankton does not significantly influence the concentration of the chemical in the top predator.

Figure 7 also indicates that for $f > 1$, there can be a substantial magnification of the effect of food chain transfer. Values of f of about 2 to 3 can result in one to two orders of magnitude increase in the food chain magnification. The principal reason for this behavior can be seen by assuming that

$$(26) \quad (dw/dt)/w = a'C$$

where a' is an overall biomass conversion efficiency. Then the food chain transfer number is

$$(27) \quad f = \frac{\alpha C}{K + a'C}.$$

Now suppose $K \ll a'C$ (the case for substances such as PCBs with low excretion rates), then

$$(28) \quad f = \frac{\alpha}{a'}.$$

This equation simply states that the change in the concentration of the chemical due to predation on contaminated food is the ratio of the assimilation efficiency of the ingested chemical to the gross weight conversion.

Figure 7 therefore provides a theoretical basis for chemical magnification in the food chain. A food chain transfer number greater than one, which is representative of high chemical assimilation and low excretion, coupled with several passes through lower level compartments can result in increases of one or more orders of magnitude in the food chain multiplier. Conversely, if the transfer number is generally less than one, then the assimilation of the chemical may be low, excretion rate high, or a combination of both low assimilation and high excretion. The multiplier, Γ, then becomes progressively smaller than unity and the body burden of the top predator does not depend significantly on the lower levels of the food chain and is only dependent on direct uptake from the water.

Estimation of Parameters

The parameters for the above model are:

a) consumption, respiration, conversion efficiency, and growth rate;

b) uptake from water, excretion rate, and contaminant assimilation.

In principle, all parameters can be estimated independently of the field data through laboratory measurements.

For the first group, considerable information exists on respiration rates, rates of weight gain, and conversion efficiencies. All are of course species, age, and temperature-dependent functions of local habitat and associated food carrying capacity. A very approximate estimate of the growth,

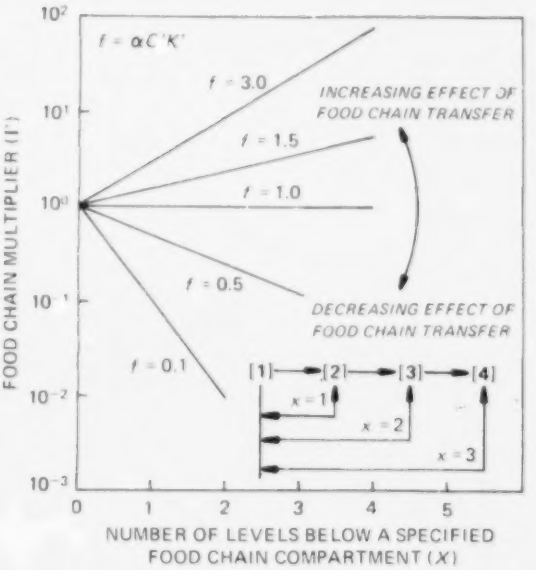

FIG. 7. Effect of constant food chain transfer number, f on food chain multiplier Γ.

Eq. (9), as a function of organism size, can be derived from the data compiled by Sheldon et al. (1973) as

$$G = 14\, L^{-0.66} \text{ @ } 25°\text{C}$$
$$= 4.2\, L^{-0.66} \text{ @ } 10°\text{C}$$

for L in μm and G in d^{-1}. For an allometric relationship of

$$L = 50\,000\, w^{0.33}$$

with w in g(w), the net weight change as a function of organism weight is

$$(29a) \quad G = 0.01\, w^{-0.22} \text{ (@ } 25°\text{C)}$$
$$(29b) \quad = 0.002\, w^{-0.22} \text{ (@ } 10°\text{C)}.$$

G can also be estimated from $(dw/dt)w$, if information is available on the weight of the organism as a function of age. With an estimate of the net weight change, C the average food consumption can be estimated from Eq. (9) if the respiration and conversion efficiency are known and assumed constant, i.e.

$$(30) \quad C_{t,t-1} = \frac{G_t + r_t}{a_{t,t-1}}.$$

A variety of data exist on the respiration rate of aquatic organisms and the relationship of respiration to body weight. Norstrom et al. (1976) discuss and summarize much of the available literature. For routine metabolism,

$$(31a) \quad r = 0.036\, w^{-0.2} \text{ @ } 25°\text{C}$$
$$(31b) \quad = 0.014\, w^{-0.2} \text{ @ } 10°\text{C}$$

for r in d^{-1}. The total metabolic rate also includes energy

TABLE 5. Assumed growth and feeding parameters.

Trophic level	Assumed range of wt-(g(w))	G, net wt change (1/d)[a]	r, wt loss rate (1/d)[b]	a, food conversion eff. (g/g)	Food consumption (g/g-d)[c]
2	0.001−1	0.0092	0.075	0.8	0.105
3	0.05−50	0.0048	0.0087	0.8	0.017
4	5−5000	0.0018	0.0055	0.8	0.009

[a]Assigned from ranges computed from Eq. (29a) and (29b).
[b]Assigned from ranges computed from Eq. (31a) and (31b).
[c]Calculated from Eq. (30).

expenditures for growth-related activities such as foraging, and Norstrom et al. (1976) have discussed the further expansion of Eq. (31) to incorporate these metabolic functions. For the overall purposes here however, Eq. (31) serve as a useful first approximation.

The conversion efficiency, a, is also species and temperature-dependent but for this work, a constant value of 0.8 is assigned following Norstrom et al. (1976).

For those parameters that are specific to the chemical, laboratory measurements can be obtained of uptake, excretion, and chemical assimilation rates. For most purposes, however, experimental data are sparse for the top predators, especially adult fish and for the intermediate levels of the food chain.

Some attempts can also be made to relate these chemical parameters to more fundamental quantities such as water solubility or octanol−water partition coefficients (Kenaga and Goring 1978; Neeley et al 1974). Such attempts, however, specific to fish and not the lower levels of the food chain, are for water uptake only and the ratio k_u/K rather than the individual parameter. (As can be seen from the model equations, it is necessary to separate k_u and K and only if clearance experiments are carried out can the individual parameters be estimated.)

Measurements of the excretion rate have been carried out for a variety of substances and have been summarized by Thomann (1978).

It appears that little fundamental work has been carried out relative to the assimilation of contemporary chemicals from ingested food, although data do exist for some substances such as the radionuclides and heavy metals.

The procedure for model calibration then is to estimate the food chain feeding parameters from the known relationships in the literature. For a given chemical such as PCBs, estimate the uptake and excretion and assimilation ratio. With the estimated parameters, calculate the food chain response with the above model, using PCB as a calibrating variable.

Following a similar procedure and without changing the food chain feeding parameters, calculate the ^{239}Pu and ^{137}Cs distribution using estimates of uptake, excretion, and assimilation.

Model Calibration: PCB, ^{239}Pu, and ^{137}Cs

The simple steady state model of Eq. (21) can now be applied to the bioaccumulation data on PCB, ^{239}Pu, and ^{137}Cs discussed earlier. The first step is to choose a representative set of parameters for the food chain shown in Fig. 5.

TABLE 6. Assumed PCB uptake, excretion, and assimilation efficiency parameters.

Food chain level	PCB ($K' = 0$)				PCB ($K' \neq 0$)			
	k_u[a]	K[b]	N'_w[c]	α[d]	k_u	K	N'_w	α
1	—	—	$10^{5.50}$	—	—	—	$10^{5.50}$	—
2	753	0	$10^{5.60}$	0.9	753	0.01	$10^{5.29}$	0.9
3	86	0	$10^{4.85}$	0.9	86	0.004	$10^{4.59}$	0.9
4	55	0	$10^{5.09}$	0.9	55	0.001	$10^{4.90}$	0.9

[a]Uptake rate (g/g(w)−d).
[b]Excretion rate (1/d).
[c]Bioconcentration from water only (g/g(d)÷g/g) = k_u/K'.
[d]Assimilation efficiency of microcontaminant.

Food Chain Parameters

Following the estimating equation for net weight change, respiration, and food consumption, a range of weights was assigned to each feeding compartment. For this range and the temperature range from 10 to 25°C, values for G and r were assigned. For a fixed conversion efficiency of 0.8, the average food consumption was calculated from Eq. (30). The assigned and computed values are shown in Table 5. These are obviously not uniquely determined values but are meant to be broadly representative of organism behavior at the lower, intermediate, and upper levels of the food chain.

The choices shown in Table 5 represent a food chain typical of phytoplankton, detritus —> large crustacean —> small fish (300 mm) —> top predator.

Examples of large crustaceans would be *Mysis relicta* as in Lake Michigan or large *Neomysis mercedis* (>10 mm) in the Sacramento−San Joaquin Delta. The crustaceans feed directly on detritus and phytoplankton and therefore form an important first link in the food chain. The small fish would represent juveniles and adults of a wide variety of fish species including alewife, perch, anchovy, and menhaden. The top predator of up to 5 kg weight is representative of a 2- to 5-yr-old striped bass or lake trout.

PCB Calibration

After assignment of the growth and feeding parameters, the PCB data shown in Fig. 1 are used to calibrate the model. Adjustments were made in the various coefficients to calibrate to the observed data, but such adjustments were always maintained within reported ranges of the coefficients. The resulting PCB specific parameters are shown in Table 6. Two cases were considered: first, a calculation assuming that the clearance of PCB is approximately zero (a case that bounds the results but also admits of some realism based on laboratory experiments by Defoe et al. 1978); secondly, a calculation assuming excretion rates as a function of size following the approximate trend for PCB given by Thomann (1978). The values for N'_w, the bioconcentration factor due to water uptake only are representative of the data shown in Fig. 1. The value of α at 0.9 has not been checked and is set at this high value because PCBs are lipid-soluble. The results of applying the model using the parameters of Tables 5 and 6 are shown in Fig. 8.

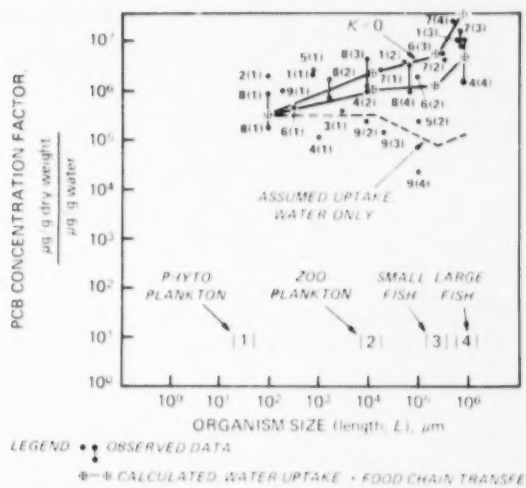

FIG. 8. Comparison of field-observed PCB concentration factors and simple food chain model calculation.

Several important points can be noted. The model calculation brackets the observed data in the upper trophic levels and hence may represent a meaningful representation of the mechanisms giving rise to the observations. In addition, for the top predator, the results in Fig. 8 for level 4 are consistent with the data shown in Fig. 2 for the Hudson Estuary. The dry weight bioaccumulation factors shown in Fig. 8 (range of N' from $10^{6.0}$ to $10^{7.4}$) are one to two orders of magnitude greater than the concentration factors used for uptake of PCBs from water only as shown in Table 6 (range of N'_{tw} from $10^{4.6}$ to $10^{5.6}$). The differences are due to food chain accumulation and are most significant at the top predator level. The decrease of N' at the top level from $10^{7.4}$ to $10^{6.6}$ reflects the inclusion of nonzero excretion rates which reduced the concentration factor by about an order of magnitude. This model indicates that for PCB, the observed concentration in the top predator fish is almost entirely due to food chain transfer and not uptake directly from the water. This result casts doubt on the adequacy of empirical relationships for PCB (or similar substances) that estimate concentration factors from laboratory experiments involving uptake of the chemical from water only. Inferences drawn from such experiments and relationships as to the potential effect on the aquatic ecosystem or human health could be in error by more than one order of magnitude.

^{239}Pu Calibration

The data on bioconcentration of ^{239}Pu directly from water are somewhat sparse. Experiments with mussels and shrimp by Fowler et al. (1975) indicated $N = 2-20$, significantly below the values for PCB. Uptake experiments of ^{241}Am by algae yielded bioconcentration factors of $10^3 - 10^4$ (Gisey and Paine 1977). Fowler et al. (1975) also determined excretion rates of plutonium of 0.0009 to 0.016 d^{-1} for the mussel and shrimp, respectively. A dependence of excretion rate on body weight of mammals has also been summarized (ICRP 1972). The reported range for mammalian livers is from 0.0006 to 0.02 d^{-1} in the 10- to 10^4-g weight interval. Values for the excretion of plutonium from the skeleton are one half to one order of magnitude less than the liver values. Data available on absorption of plutonium from the gastrointestinal tract for mammals (ICRP 1972) indicate that the values are very low and generally less than 1%. Fowler and Guary (1977), however, measured absorption efficiencies of 20–60% in crabs and suggested that the data from mammals may not be applicable to marine invertebrates. The results of the model calibration given below, on the other hand, tend to support a low absorption efficiency in aquatic food chains.

Table 7 indicates the parameter choices for ^{239}Pu. The results of the model calculation using these values are shown in Fig. 8. As shown, the calculated four orders of magnitude decrease in the bioaccumulation factor is representative of the observed data and results principally from the assumed low absorption efficiency and the excretion rates shown in Table 7. If the higher levels of Fowler and Guary (1977) are used, the calculated decline is only about one order of magnitude for the same excretion rates. The calculations compare well to the observed data at the higher absorption efficiency only if the levels of excretion are increased to values greater than 2 per day. Such excretion levels, however, appear unjustified based on the measurements of Fowler et al. (1975). One tentatively concludes therefore that the observed ^{239}Pu concentration factor behavior is due principally to low absorption of ^{239}Pu from food, and associated levels of excretion of 0.01–0.05 per

TABLE 7. Assumed uptake, excretion, and absorption efficiency parameters for ^{239}Pu and ^{137}Cs.

Food chain level	^{239}Pu				^{137}Cs					
					Freshwater		Marine			
	k_u[a]	K[b]	N_w[c]	α[d]	k_u	N_w	k_u	N_w	K	α
1	—	—	10^4	—	—	10^3	—	$10^{1.5}$	—	—
2	18.7	0.05	$10^{2.5}$	0.01	4.9	10^2	0.49	10^1	0.03	0.5
3	0.3	0.02	10^1	0.01	0.4	$10^{1.5}$	0.07	$10^{0.75}$	0.003	0.5
4	0.01	0.01	10^0	0.01	0.04	10^1	0.01	$10^{0.5}$	0.0018	0.5

[a]Uptake rate (g/g(w)–d).
[b]Excretion rate (1/d).
[c]Bioconcentration from water only (Bq/g(w)÷Bq/g) = k_u/K'.
[d]Assimilation efficiency of microcontaminant.

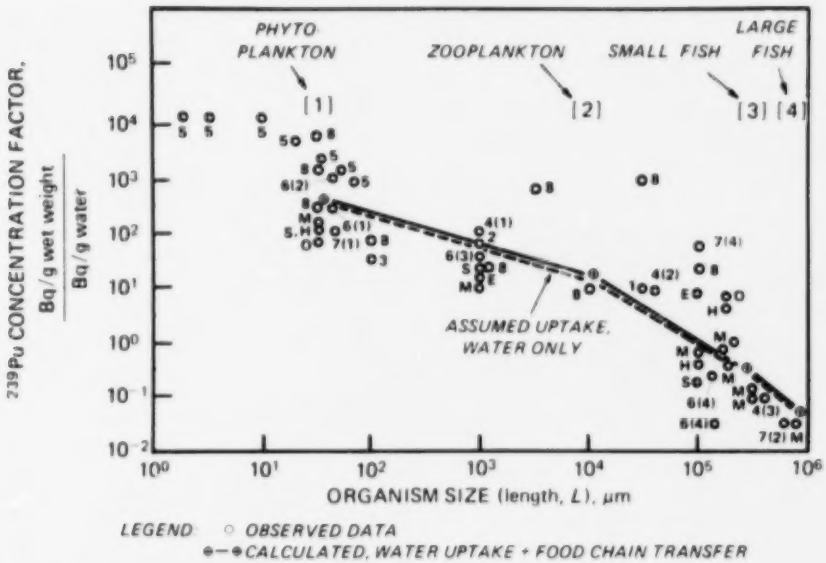

FIG. 9. Comparison of field-observed ^{239}Pu concentration factors and simple food chain model calculation.

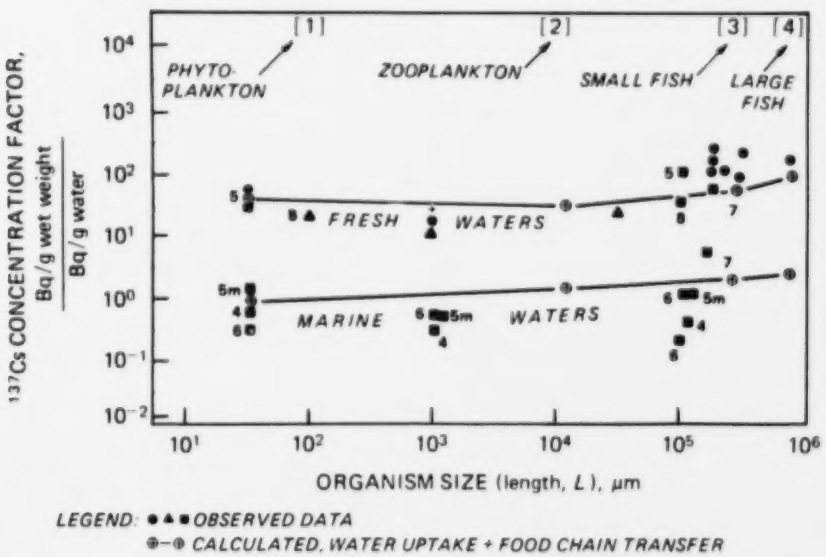

FIG. 10. Comparison of field-observed ^{137}Cs concentration factors and simple food chain model calculation.

day. Figure 9 also indicates that as a consequence, the difference between the concentration factor due to water and food and that due to water alone is insignificant. A reasonable estimate then of ^{239}Pu body burden can be obtained by a simple partitioning model that relates water concentration to body burden directly without any effect of food chain transfer.

^{137}Cs Calibration

Reported bioconcentration factors for ^{137}Cs uptake by fish and mollusks from water only range from 1 to 100 depending on organism and test conditions (Bhatt 1966; Davis 1961; Mauro 1973; Harrison 1973). Laboratory values for biocon-

centration factors for algae parallel those of the field data (range 1–100) and depend on salinity (Harvey and Patrick 1967; Gutknecht 1964; Rice 1961). Excretion data of ^{137}Cs have been summarized by Vanderploeg et al. (1975), Mauro (1973), and others. The data show a strong dependence on organism size and the following relationship was used to estimate the excretion rate:

$$(27) \quad K = 10\, L^{-0.625}$$

for L in μm and K in d^{-1}. Hewett and Jeffries (1978) measured absorption of ^{137}Cs from food at 42% for plaice and 67% for trout, and Mauro (1973) has summarized efficiencies for several species of fish feeding on various food sources and reports a range from 3% for bluegill on detritus to 92% for bluegill on chironomid larvae; Table 7 shows the choice of parameters for uptake, excretion, and absorption. Two levels of bioconcentration factors for uptake directly from the water were chosen to represent the freshwater and marine cases.

The results of the calculation and the comparison to the observed field data are shown in Fig. 10. The increase in the bioaccumulation factor is not marked from the phytoplankton to the top predator in either case, although for both cases, the ^{137}Cs body burden at the top of the food chain is due principally to the food route. The calculation indicates that the initial salinity-dependent sorption by the phytoplankton dominate the result at the top predator level. For the freshwater case, 91% of the calculated ^{137}Cs accumulation factor at the fourth level is due to the phytoplankton and for the marine case, 70% is due to the phytoplankton. The ^{137}Cs case therefore is of interest since it represents an example of intermediate accumulation, the level of which is strongly dependent on phytoplankton sorption.

Conclusions

It is concluded from this work that a simple steady state model of transfer of chemicals in the food chain can aid in explaining the observed concentration factors for three substances that exhibit widely varying behavior in the food chain. The simple steady state model indicates that the parameters of food assimilation, excretion, and net weight gain are important characteristics that determine the degree to which a chemical bioaccumulates in the food chain. For a substance such as PCB, the data and the model analyses indicate that at the top predator level, almost all of the observed body burden can be attributed to the transfer of PCBs from contaminated food. The bioaccumulation is due to the postulated relatively high adsorption of the PCB from the contaminated food and the relatively low excretion of PCB from the upper levels of the aquatic ecosystem. Some exceptions in specific food chains, however, do exist. For a substance such as ^{239}Pu, the data and model analyses indicate that the effect of food chain transfer is insignificant and the observed body burden, in the upper level of the food chain, is due almost entirely to direct adsorption from the water. The application of the analysis to ^{137}Cs indicates concentration factors that are at an intermediate level between PCB and ^{239}Pu. The observed cesium concentration factors are due principally to food chain transfer with a high dependence on the salinity-dependent phytoplankton adsorption.

The analysis of data, coupled with the steady state model, indicates that a specific microcontaminant behaves in a surprisingly similar manner across diverse food chains. The analysis, however, is an order of magnitude, analysis and individual food chains may vary from the average, although across the entire spectrum of freshwater, lake, estuarine, and open marine systems, the behavior of PCB, ^{239}Pu, and ^{137}Cs can be explained by similar principles.

The simplified model of chemical accumulation in the food chain can, therefore, be of specific value in assessing the relative effect of the food route versus the water route in the chemical body burden for the upper levels of the food chain. The analysis indicates that for substances such as PCBs, the actual field concentration in the top predator may be at least one order of magnitude higher than presently assumed from the results of laboratory uptake data. The framework also indicates the need to obtain information on chemical absorption efficiencies and excretion rates especially for the top predators and also for the intermediate levels of the food chain.

To first approximation then, the accumulation of chemicals in the food chain may, through the use of a steady state model, be calculated and forms a basis for estimating the allowable discharge of a substance so as not to exceed a given concentration in the food chain. The food chain transfer number and the food chain multiplier are simple approximations to a complex system but illustrate the basic approach that can be used in assessing the potential buildup of a chemical in a food chain. For any specific food chain, however, more detailed compartment analyses must be carried out.

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